

A Reactionless Precision Pointing Actuator

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This paper discusses the applications, design, control and testing of an actuator that provides the precise motion control of a gimbal platform without torquing against the basebody to which it is attached. The reactionless actuator described in this paper has been given the name "reactuator".

INTRODUCTION

The Voyager 2 spacecraft built by the Jet Propulsion Laboratory (JPL) flew by Uranus in January of 1986 and took spectacular high resolution pictures of its rings and moons. Due to the long exposure times required, the entire spacecraft was slewed to compensate for the relative motion between the spacecraft and the image. Voyager's cameras are mounted on a two axis gimballed platform which is controlled by two geared actuators. Voyager was not able to take advantage of the platform for image motion compensation since the actuators induce vibrations in the spacecraft which feed back and blur the camera images. A minimum of 30 seconds must be allowed for the spacecraft to settle down after a low rate slew of the platform before high resolution, no smear pictures can be taken. Experience with Voyager and other spacecraft has led JPL to pursue the development of reactionless gimbal actuators for the precise positioning of gimballed platforms [1,2,3]. An actuator of this type has been designed for a Space Shuttle based tracking system and is currently baselined for the Mariner Mark II class of interplanetary spacecraft [4].

In addition to exciting a spacecraft's flexible modes, the angular momentum imparted to a gimballed platform by a conventional direct drive or geared actuator induces a rotation of the whole spacecraft. This rotation must be taken out by the spacecraft's attitude control system. For example if the Mariner Mark II spacecraft had a conventional gimbal actuator an additional 50% of fuel beyond that required for attitude control would be needed to take out actuator induced rotation of the spacecraft [5]. The reactuator, on the other hand, decouples motion of the gimbal from the spacecraft. Gimbal control is independent of the spacecraft natural modes and spacecraft attitude control is independent of gimbal motion.

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REACTUATOR SCHEMATIC

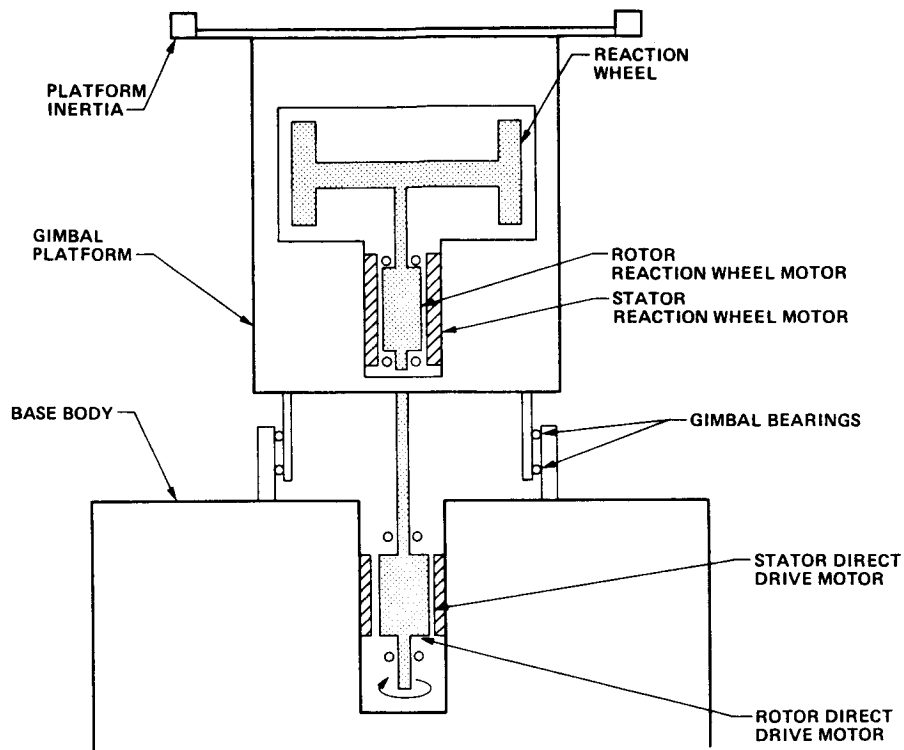


Figure 1

HARDWARE DESCRIPTION

There are two rotational loads imposed on a gimbal moving relative to a basebody: the inertial load and the loads in the joint imparted by bearing friction and cable torque between the gimbal and basebody. The reactuator shown schematically in Figure 1 has two motors to account for these loads. The reaction wheel (RW) motor cancels inertial loads and the direct drive (DD) motor handles loads in the joint. By properly distributing torque commands to each motor, the gimbal can be moved without imparting a reaction torque on the basebody. Providing a rigid body to torque against the reaction wheel permits high bandwidth platform control even if the gimbal is mounted on a flexible structure. The direct drive motor replaces the energy lost due to bearing friction and cable torque thereby preventing the reaction wheel from spinning up and saturating in speed.

In addition to two motors, the reactuator incorporates two angular position sensors as shown in the detailed cross section of Figure 2. The

sensors provide commutation signals for the brushless DC motors as well as position and velocity feedback for closed loop rate control. The components of the reactuator have been carefully selected to minimize self induced torque ripple. A detailed description of each component follows.

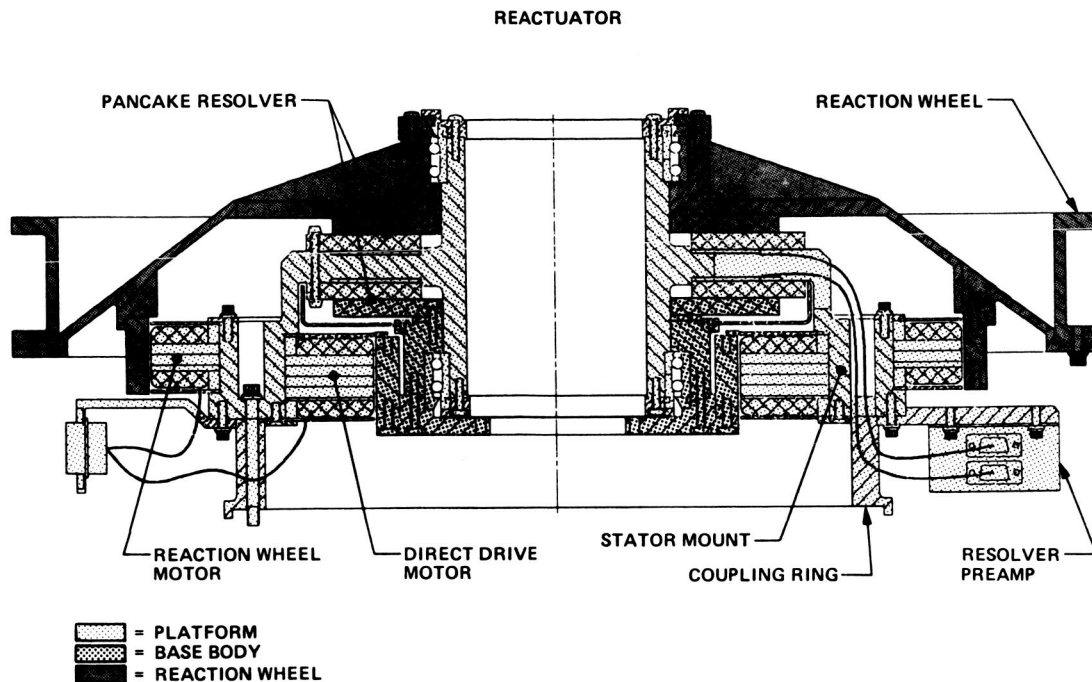


Figure 2

Bearings

The reaction wheel and gimbal are each supported on a duplex pair of stainless steel ball bearings. The bearings have a solid outer race and split inner race with customized preload, contact angle and raceway curvature. The reactuator housing is made of titanium to closely match the bearing's thermal coefficient of expansion.

Resolver

The position sensors are high accuracy ($\pm 29 \mu\text{rad}$) printed circuit pancake resolvers. Each resolver has two tracks, one with 256 poles and one with 254. The outputs of the two tracks are converted to 12 bit digital words by two hybrid resolver to digital converters [6] which also output an analog velocity signal. The digital words from the two tracks are correlated digitally to produce a 19 bit word that corresponds to

absolute position over one revolution. A built-in ferrite core transformer [7] allows the resolver to be interfaced to the stationary element. This eliminates the need for a slip ring or separate rotary transformer.

Motors

Two phase, 16 pole, brushless DC motors provide actuating torque for both the reaction wheel and the direct drive. The motors are designed to generate a sinusoidal back EMF signal with minimum harmonic distortion. Cogging torque is minimized by the use of a nickel iron lamination material.

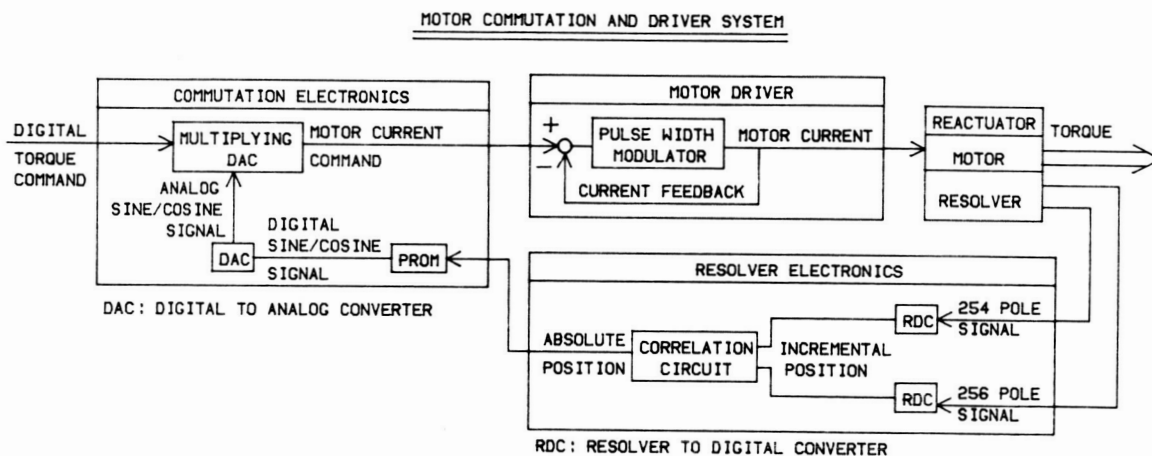


Figure 3

Motor Driver

The motor commutation and driver system is a hybrid of digital and analog circuitry as shown in Figure 3. It is designed to drive the motor with sinusoidally varying current resulting in minimum torque ripple. The digital absolute position signal from the resolvers addresses a sine signal that is stored in programmable read only memory (PROM). The output of the PROMs is converted into an analog signal and fed into a multiplying digital to analog converter (DAC). A digital torque word modulates the amplitude of the analog commutation signal and feeds it to a pulse width modulated (PWM) power amplifier [8]. The PWM driver is a closed loop amplifier that produces a current proportional to the commutation signal based on sensing and feeding back output current. The driver automatically compensates for variations in supply voltage as well

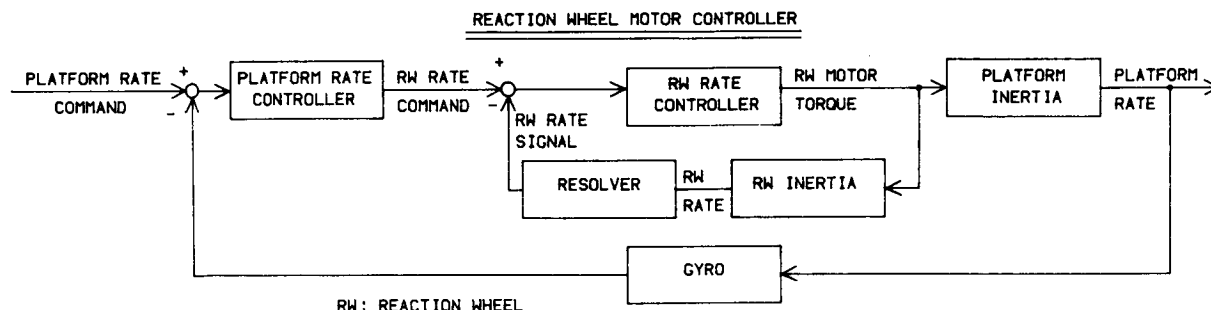


Figure 5

Reaction Wheel Motor Controller

The reaction wheel motor controller incorporates two loops as depicted in Figure 5. The outer loop compares the platform rate as measured by the gyro with the rate command. The resulting error signal goes through a filter which produces the reaction wheel rate command for the inner loop. This loop compares the commanded rate to the reaction wheel resolver velocity signal and sends the appropriate torque commands to the motor causing it to follow the commanded rate. Since this velocity signal has high bandwidth and relatively low noise, the inner loop rejects motor and bearing torque ripple thus producing a smooth reaction wheel rate.

The platform rate controller has the transfer function,

$$\frac{K_P S + K_I}{s^2}$$

The two integrators of this controller guarantee no steady state error to constant platform rate commands. The reaction wheel controller transfer function consists of a simple gain that produces well damped response to the rate feedback signal.

Direct Drive Motor Controller

If the reaction wheel's speed is such as to cancel the angular momentum of the platform and the direct drive motor's torque cancels bearing and cable torque, then the reactuator will exert no torque on the spacecraft. The direct drive motor controller depicted in Figure 6 is designed to achieve this result. The controller commands the direct drive motor to provide sufficient torque to drive the angular momentum of

the reaction wheel and the platform to zero. The direct drive controller has proportional plus integral gains that produce a well damped zero steady state error response.

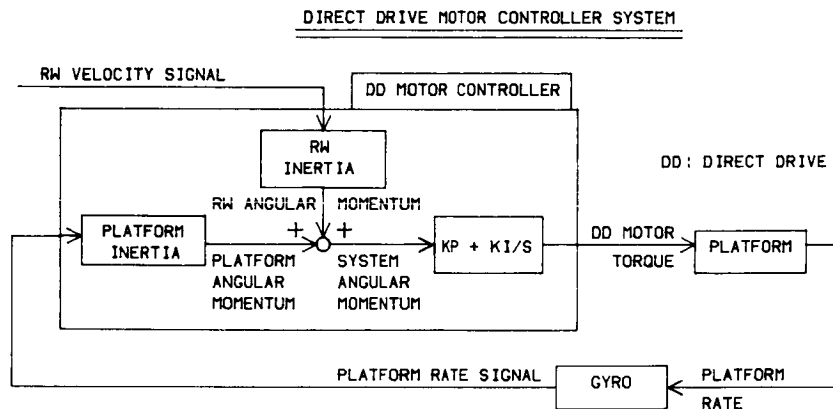


Figure 6

TESTING

A photograph of the reactuator and rate control system breadboard is shown in Figure 7. The reactuator breadboard is assembled out of JPL's Galileo spacecraft spare parts. It is mounted on an air bearing to simulate a spacecraft and to allow the effectiveness of the "reactionless" actuator to be monitored. The air bearing is isolated from ambient noise by a seismic isolation pier. Table 1 summarizes the key parameters of the breadboard system.

The system was first tested in an open loop. The air bearing was levitated and the reaction wheel motor was given a constant torque command. The gyro measured a platform disturbance of 280 $\mu\text{rad/sec}$ RMS induced by motor and bearing torque ripple. The rate loop around the reaction wheel motor (Figure 5) was closed to attenuate this disturbance. Again the air bearing was levitated but this time a constant rate command was given to the reaction wheel motor controller. The closed loop platform rate disturbance measured by the gyro was 12.3 $\mu\text{rad/sec}$ RMS. Integrating the velocity signal, the corresponding disturbance in terms of position was 7 μrad RMS. Comparing the open to closed loop platform response indicates that the controller exhibits a -27 db disturbance rejection to reaction wheel motor and bearing torque ripple [9].

REACTUATOR BREADBOARD SYSTEM

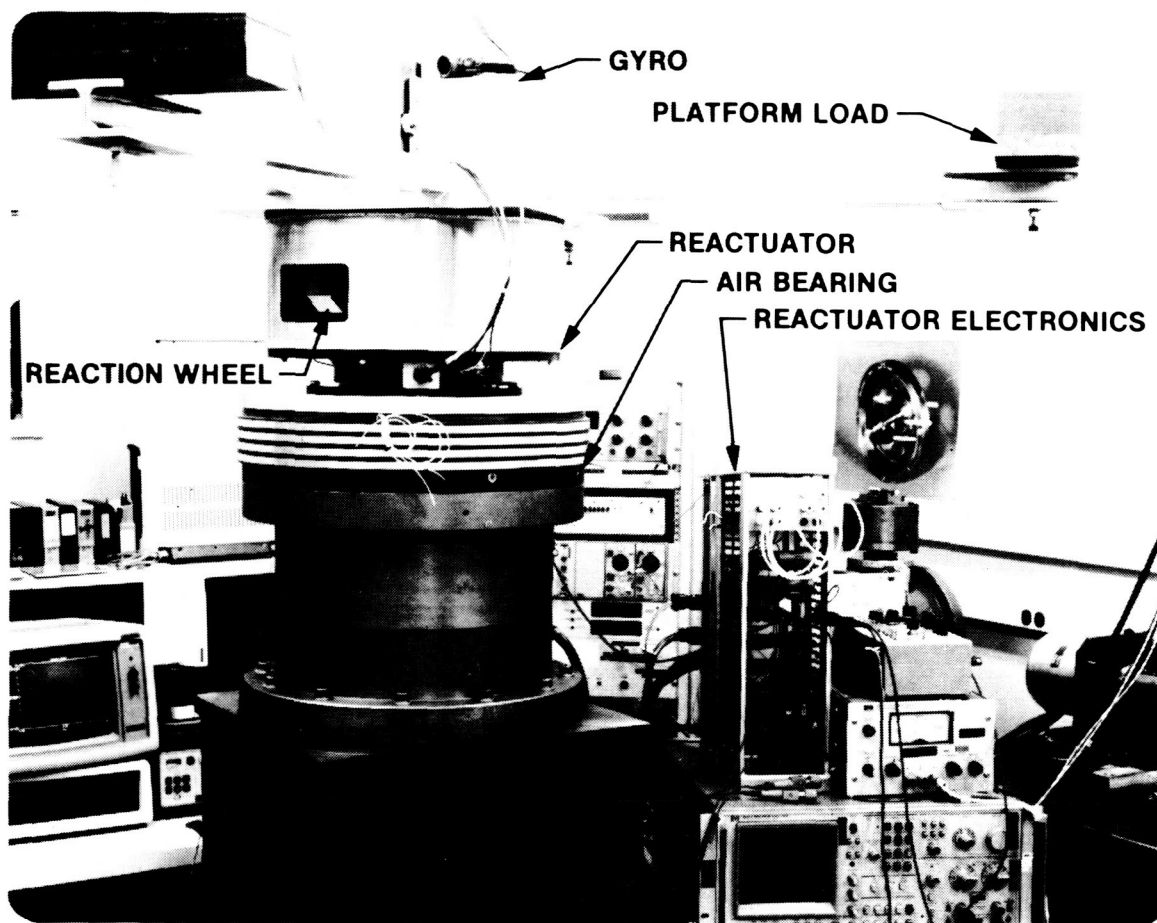


Figure 7

The breadboard reactuator is connected to the electronics by numerous cables. The torque from these cables causes the reaction wheel to accelerate until the motor torque saturates due to the back EMF generated by the motor. The direct drive motor controller which prevents the reaction wheel motor from saturating will be incorporated in the near future. The two motor actuator will then be tested to determine the effectiveness of the "reactionless" actuator. A flexible boom will be attached to the air bearing and the ability of the actuator to control the platform without exciting this boom will be determined. The flexible boom will also be used to intentionally induce basebody disturbances allowing the reactuator to demonstrate its ability to reject basebody disturbances.

TABLE 1

Breadboard Reactuator System Parameters

Gyro bandwidth	5.5 hz
Gyro peak rate	35 mrad/sec
Gyro noise	23 rad/sec RMS
Resolver bandwidth	30 hz
Resolver noise	4.6 mrad/sec RMS
Resolver peak rate	11.9 rad/sec
RW and DD motor drive voltage	45 volts
RW and DD motor driver bandwidth	400 hz
RW motor torque constant	5.21 Nm/amp
RW motor winding resistance	21.3 ohms/phase
DD motor torque constant	1.25 Nm/amp
DD motor winding resistance	33 ohms/phase
Platform inertia	56 Kg m ²
RW inertia	0.281 Kg m ²

RW: Reaction Wheel

DD: Direct Drive

CONCLUSION

It is practical to consider a reactionless actuator for the precise pointing of a gimballed platform on a basebody which has either low structural stiffness or a low moment of inertia. An actuator of this type allows the design of the gimbal controller to be completely independent of the basebody's structural dynamics. There are many applications for a reactionless actuator including the Space Station where it will be critical to precisely point various payloads without exciting the station's low frequency modes [10].

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